Cosmological Surveys
From the Radio to Sub-millimeter
(with focus on centimeter)

Steven T. Myers (NRAO)

**National Radio Astronomy Observatory, Socorro, NM*

Launchpoint

- With new observational facilities, instruments and surveys coming online this decade and next, we will observe galaxies near and far
  - galaxies are full of incendiary gas, abrasive dust grains, noxious chemicals, and nuclear waste…
- But, we want to use them as a force for good
  - COSMOLOGY!!!
- I will describe opportunities in the radio to sub-mm part of the spectrum

Astro2010: A Game of Questions

Astro2010 Decadal Survey:
One of the worst Massively Multiplayer Online (MMO) games ever!

- The Themes
  - Cosmic Dawn
  - Physics of the Universe
  - Discovery, Origins, Cosmic Order, Frontiers of Knowledge
- The Questions
  - How do cosmic structures form and evolve?
  - Why is the universe accelerating?
  - What is the fossil record of galaxy assembly and evolution from the first stars to the present?
  - How do baryons cycle in and out of galaxies and what do they do while they are there?

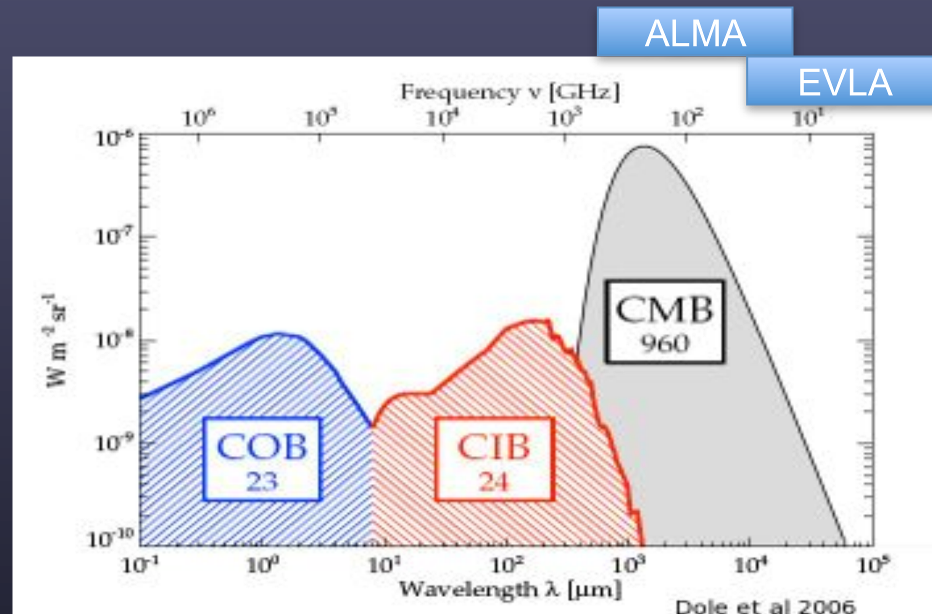
Radio: A multi-purpose waveband for all!

Radio astronomy in a Nutshell

Thermal & Non-thermal radiation processes

Freq.

- Synchrotron emission. MeV-GeV electrons. HE astrophysics
- Plasma propagation phenomena (dispersion, Faraday rotation, interstellar scattering)
- Hyperfine atomic hydrogen line
- Thermal bremsstrahlung (ff) and atomic recombination lines
- Coherent maser lines
- CMB and SZE
- Thermal dust continuum
- Molecular rotational lines (CO)
- Atomic cooling lines (e.g. redshifted C+ at 158 um)

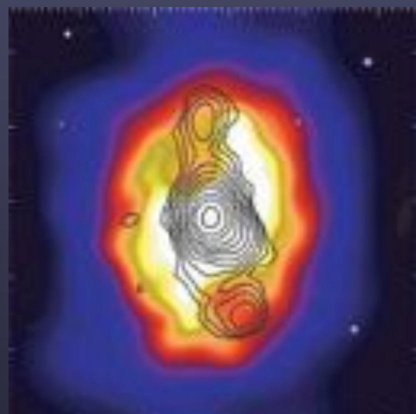


- Radio window is 10 MHz to1THz i.e. five orders of magnitude
- Millimeter/submillimeter photons are the most abundant photons in the cosmic background, and in the spectrum of the Milky Way and most spiral galaxies.

Radio Science Driven By Four Themes

Magnetic Universe

Measure the strength and topology of the cosmic magnetic field.



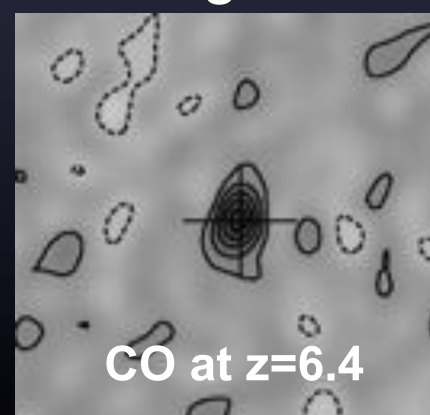
Obscured Universe

Image young stars and massive black holes in dust enshrouded environments.

Transient Universe

Follow the rapid evolution of energetic phenomena.

Evolving Universe



Study the formation and evolution of stars, galaxies, AGN, and the Universe.

Disclaimer

- What I will not talk about …
  - Cosmic Microwave Background
  - Sunyaev-Zeldovich Effect
  - Pulsars as probes of long-wavelength Gravity Waves
  - Tomography of the Hydrogen Epoch of Reionization

e.g. the stuff cosmologists are usually keen on

(hopefully others will discuss these during workshop)

- What I will (briefly) talk about …
  - Tools for large-area Radio Galaxy surveys
  - Stuff that affects galaxy formation and/or evolution
  - Stuff that serves as signposts of distant Universe

Evolving Universe: Radio Cosmology

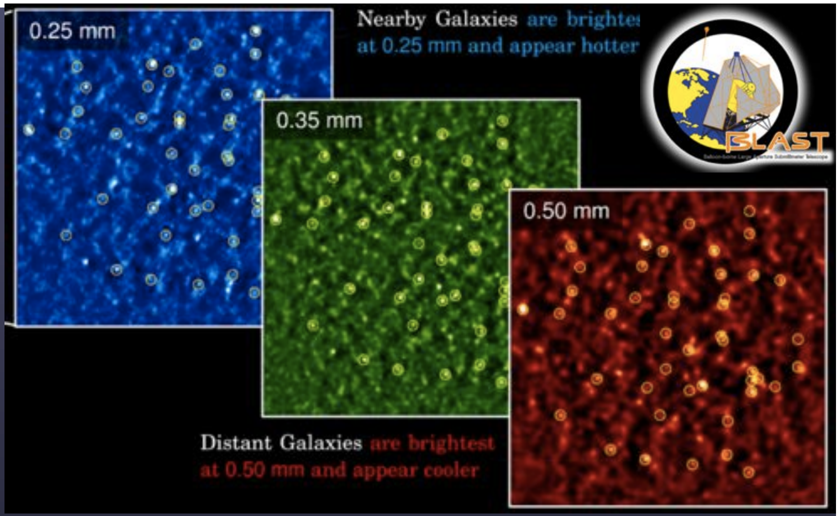
- Cosmological Galaxy Surveys
  - identify and count galaxies (traditional survey)
    - Spectra for 10^4 - 10^9 galaxies to z > 1.5 in > Gpc volume
  - cosmological parameters
    - "Dark Energy" (DE) via H(z) measurements (BAO &c)
  - growth of structure (counts, galaxy evolution)
  - a large galaxy database for (ga)strophysical studies
  - alternative: "intensity mapping" (angular power spectrum)
- Also Continuum Photometry
  - synchrotron / free-free in Milky Way-like galaxies
  - weak lensing studies (DE), AGN/SMBH surveys
  - explosive/descructive events (GRB,SNe,TDE,flares)

The Probes: Key UFIR Lines

- 1 - Atomic Hydrogen (weak transition)
  - "21cm" HI line (rest 1.42 GHz, z=1.5 at 568 MHz)
  - single line in "clean" part of spectrum
    - single line redshift determination almost assured
- 2 - Molecular CO (strong transition)
  - CO ladder (1-0 rest 115.27 GHz, z=1.5 at 46.11 GHz)
  - whole J ladder of lines (115,230,345,460…)
    - no ambiguity in redshift if multiple transition seen
  - forested area of spectrum
    - danger: many weaker lines could contribute to correlated signal
- 3 - High-J CO and C+
  - ALMA, LMT, CCAT

Launchpad: High Redshift Galaxies

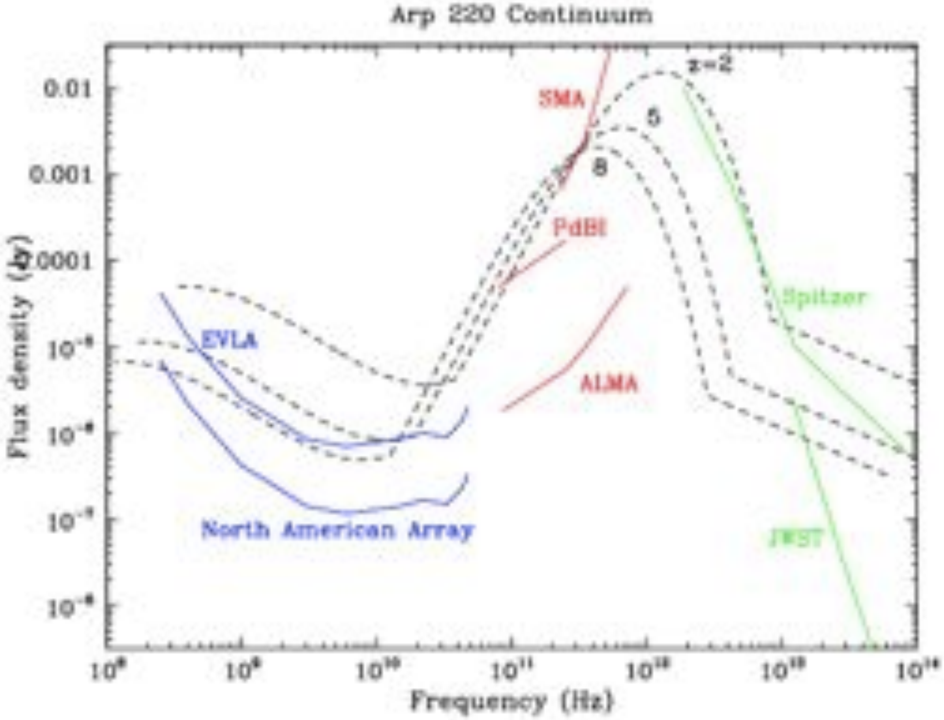
- mm/sub-mm/IR
  - dusty galaxies, ULIRGS,
  - we have the ABCs:
    - ALMA, BLAST, CARMA, CCAT, …
    - and ACT, APEX, …

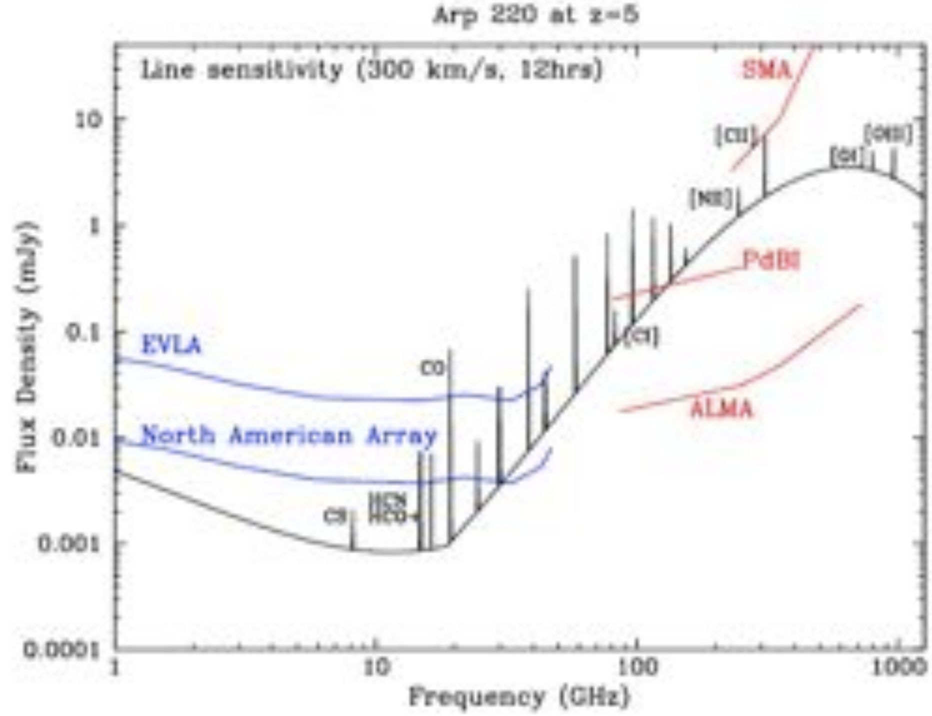


- sub-m (HI)
  - local universe z<0.2: Arecibo, EVLA, GBT, Parkes, &c
  - GBT correlation with O/IR z=0.8 (Chang et al.)
  - pave the way: need next-gen facilities for high-z
- our departure point: cm
  - <u>redshifted CO lines (EVLA, GBT), continuum</u>

Landscape: Galaxy Spectra

- Lines and continua of star-forming galaxies
  - canonical source Arp220



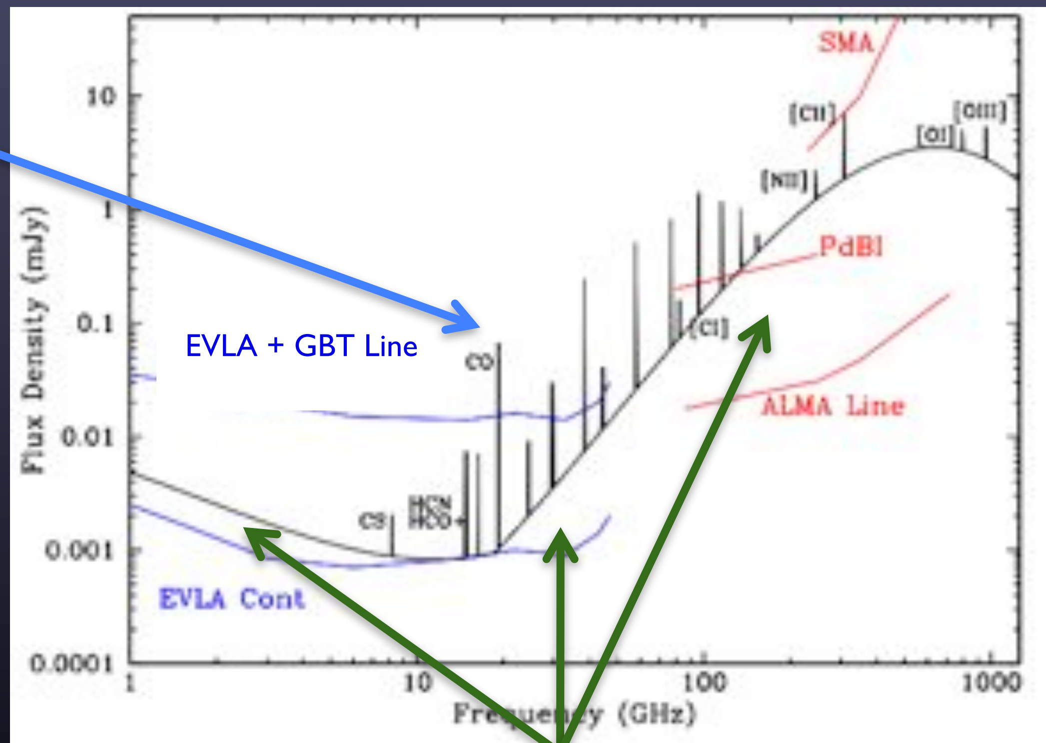


From Myers et al. NAA Astro2010 white paper

Line & SED Probes for Galaxy Evolution

SED of galaxy forming 100 M_{sun} yr^{-1} at $z=5$

Low-J molecular lines
- Total H2
- Dense gas
- Dynamics



Continuum (dust, free-free, synchrotron)
- SFR, ISM distribution, dust abundance

ALMA

- Will be the workhorse ground-based array for millimeter and submillimeter astronomy
  - 50 x 12m main array (equivalent collecting area to VLA)
  - field-of-view (12m antenna) ~20" at 300 GHz
  - 4 x 12m single dishes (for large-scale mapping)
  - 12 x 7m compact array (for large-scale mapping)

ALMA

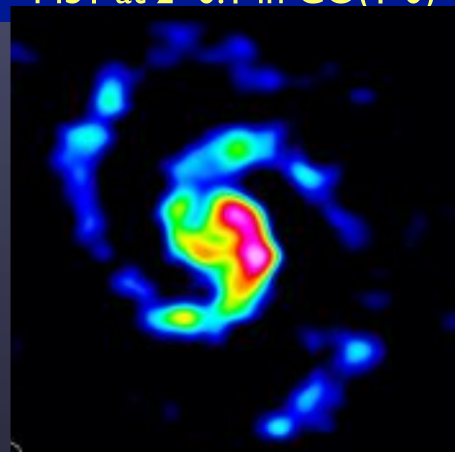
- Will be the workhorse ground-based array for millimeter and submillimeter astronomy

  - 14 antennas at high site (5000m) in 2011 (now 33 in 4/12)

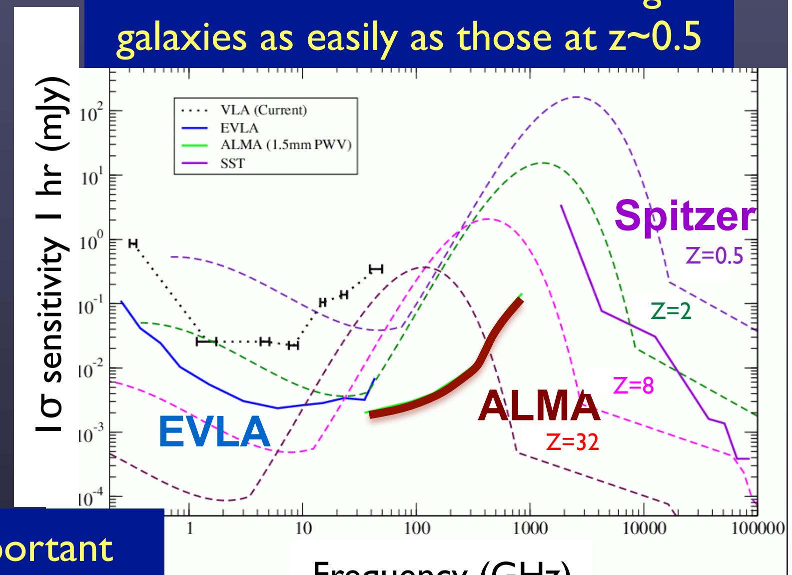
ALMA Science: Extragalactic

- Detailed imaging of dust and gas in nearby galaxies
- Probing the nature of AGN, black holes, GRBs and other transient phenomena
- Imaging dust and gas from high redshift galaxies

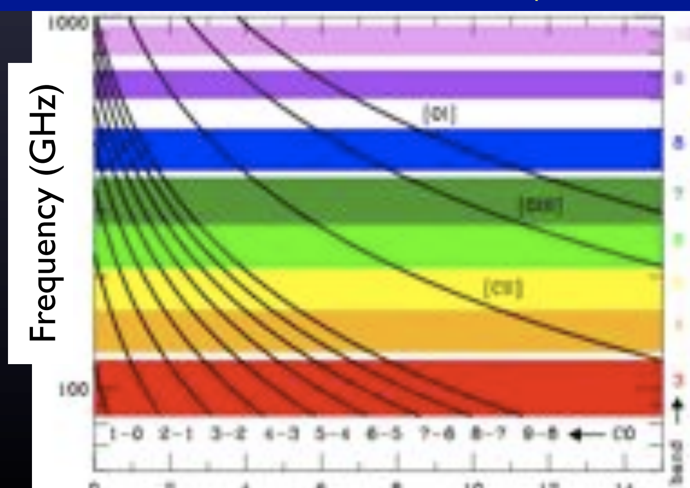
4 hr CASA Simulation of M51 at z=0.1 in CO(1-0)



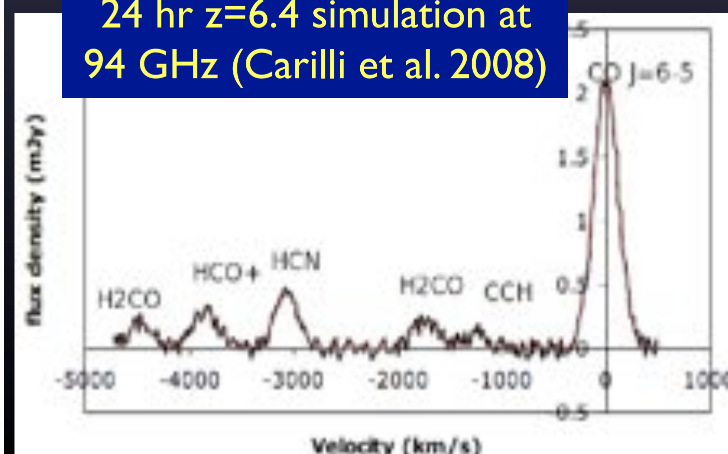
Detect dust continuum from high-z galaxies as easily as those at z~0.5



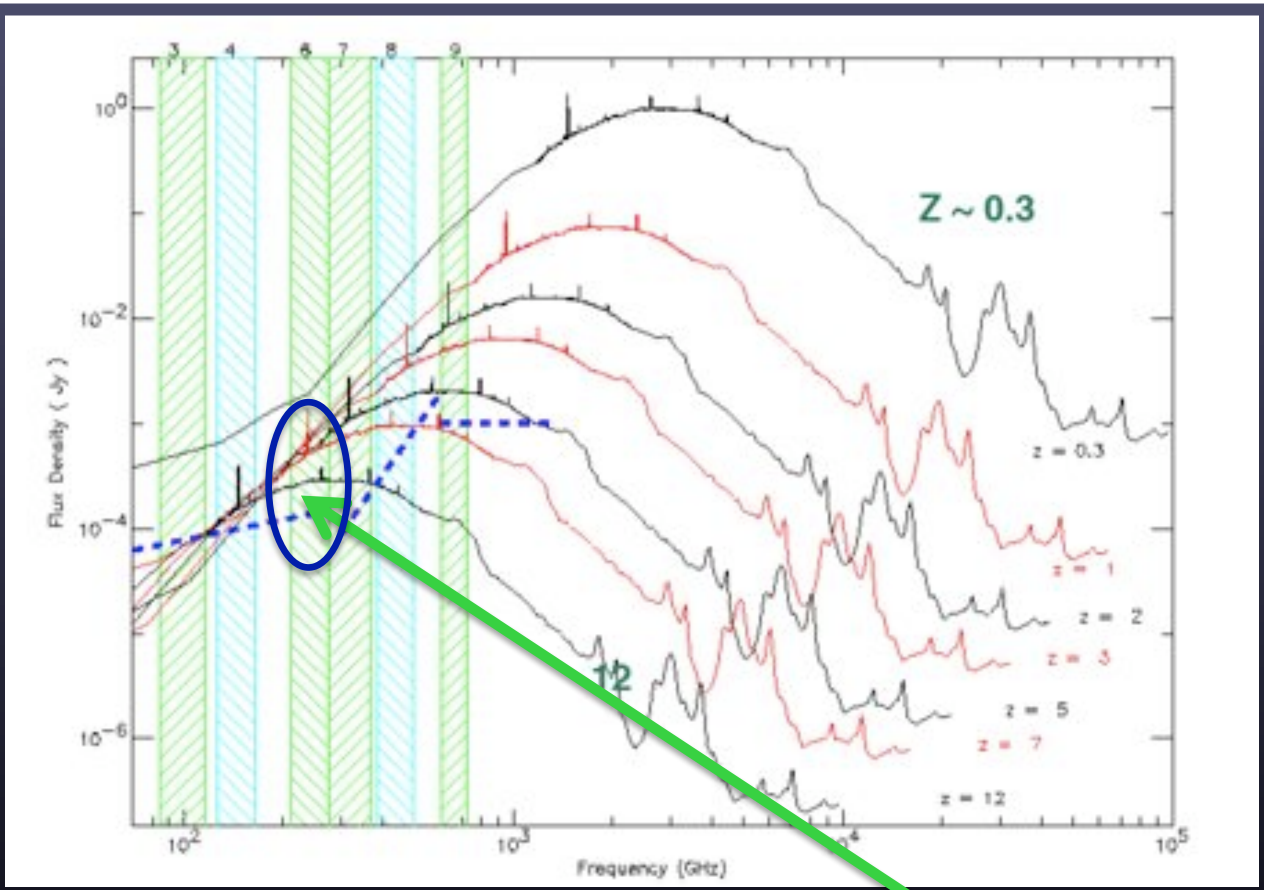
Nearly continuous coverage of important lines as a function of redshift (Maiolino 2008)



24 hr z=6.4 simulation at 94 GHz (Carilli et al. 2008)



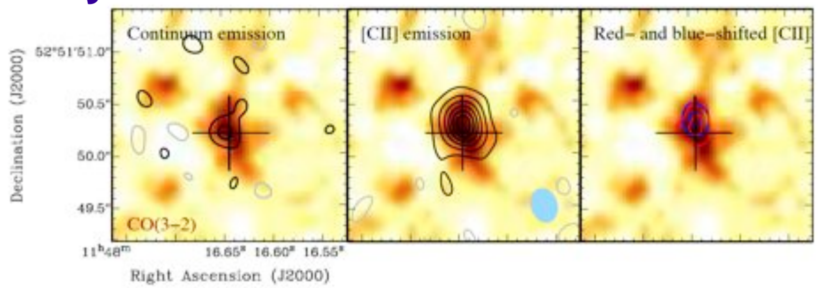
ALMA: dust emission from galaxies



"Sub-millimeter Galaxies" - fluxes are nearly distance-independent in the sub-mm

ALMA: CO, [CII], dust across the universe

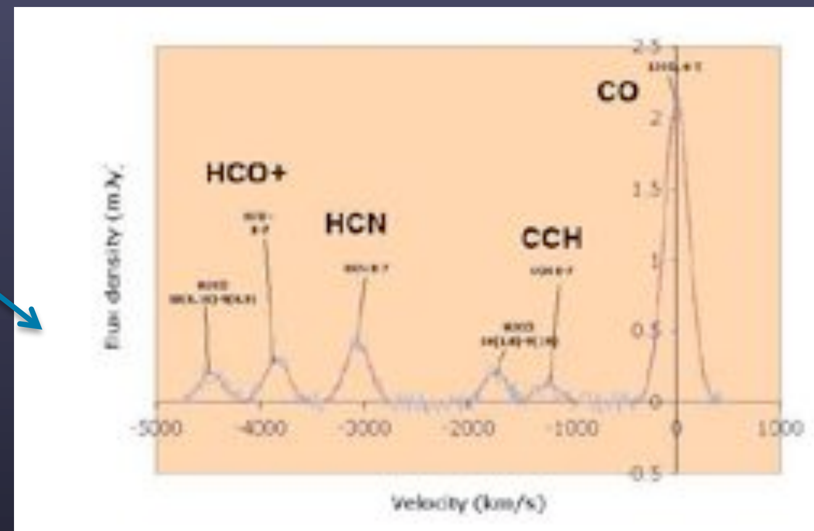
J1148+5251 PdBI ~24 hrs



dust [CII] [CII]v

z= 6.42; t = 870 Myr

J1148+5251 simulated ALMA data



high z chemistry? J1148+5251 with ALMA in 24 hrs

Carilli et al. 2007

[CII], CO, & dust in early galaxies ALMA can detect:

dust in galaxies with SFR ~100 $M_\odot$/yr at z = 5 in ~a minute

CO in galaxies with SFR ~100 $M_\odot$/yr at z = 5 in ~ a hour

CO in Milky Way-like galaxies at z=3 in ~24 hours

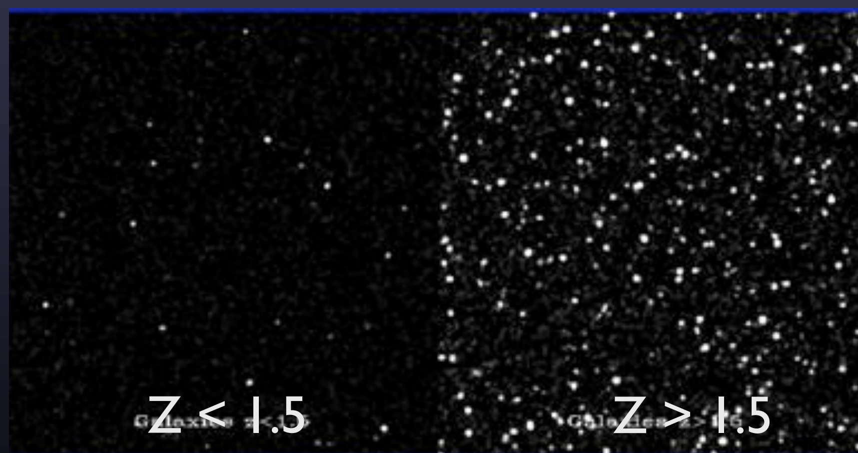
The ALMA View of the Deep Universe

Hubble Deep Field

Lanzetta+97

simulated

ALMA Deep Field



Wootten & Gallimore 01

Many ALMA SMGs will be difficult to identify optically (until JWST)

The Karl G. Jansky Very Large Array
0.058-50 GHz in 0.035-36.4 km

The Karl G. Jansky Very Large Array
0.058-50 GHz in 0.035-36.4 km

The Expanded Very Large Array

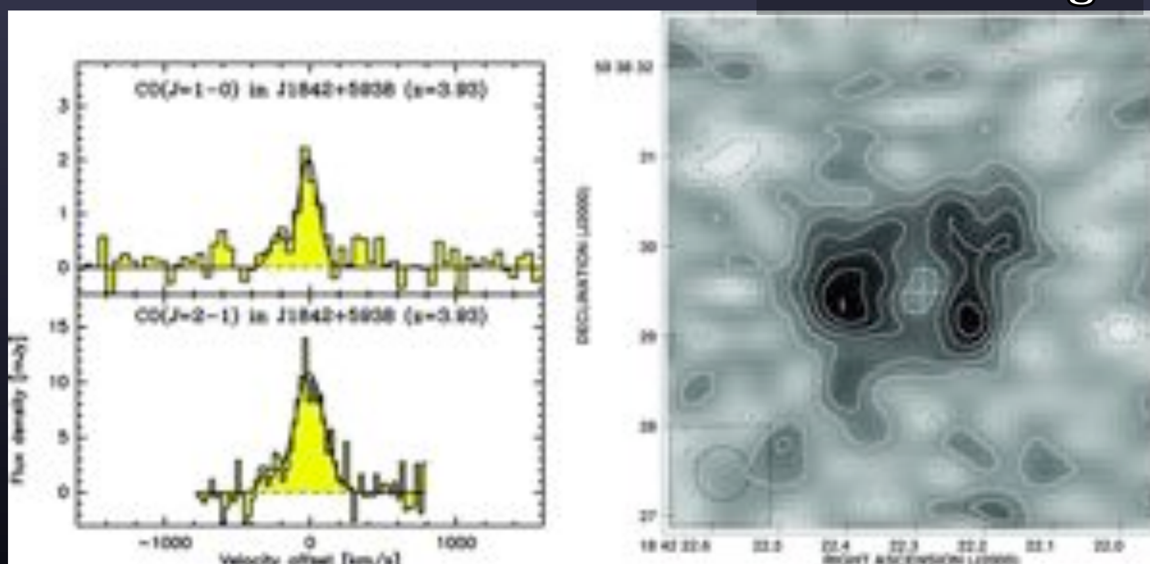
<u>…is a major upgrade of the Very Large Array</u>

- improves all capabilities of the VLA -- except spatial resolution -- by at least an order of magnitude.
  - Full frequency coverage from 1 to 50 GHz (<1 GHz in bands)
  - New digital correlator with unprecedented capabilities
  - Up to 8 GHz instantaneous bandwidth, 8K to 4M channels
  - ~100 μJy (1σ, 10sec, 1GHz) point-source continuum sensitivity at 5GHz
    - 100 square degrees to 100μJy (1σ) in 40ksec (11h) of integration
  - ~30 mJy (1σ, 1 km/sec, 10sec) line sensitivity at 5GHz
- The Project began in 2001, will be completed in 2012
  - Counting all sources, a $90M project.
  - EVLA science observing started March 2010
  - next proposal deadline Aug 1 (twice a year)

VLA Images Molecular Gas at High-z

- Image low-excitation CO from high-z galaxies
  - Wide bandwidth translates to redshift-space depth
  - Explore the formation of massive galaxies, clusters, and the evolution of cold gas reservoirs and the molecular gas fraction.

CO 2-1 Image



Molecular Einstein Ring Toward SMG MM18423+5938 (z=3.93)

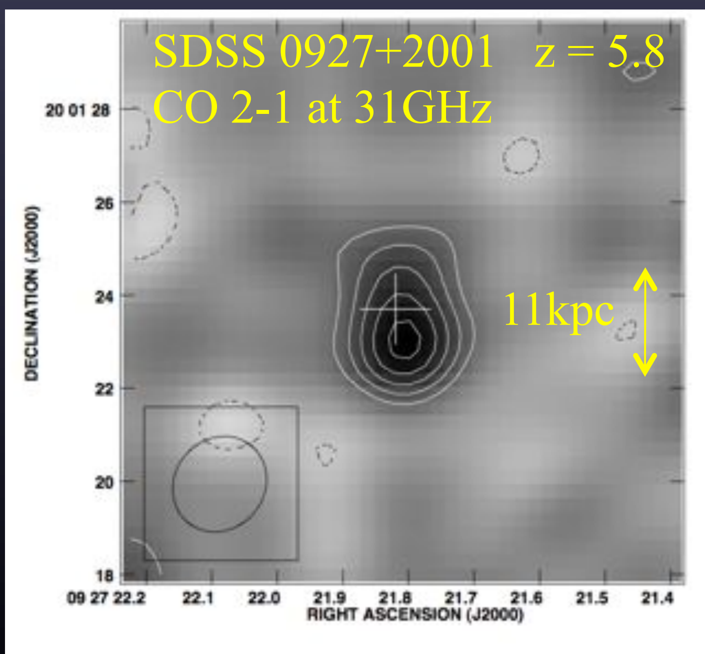
LESTRADE ET AL. (2011)

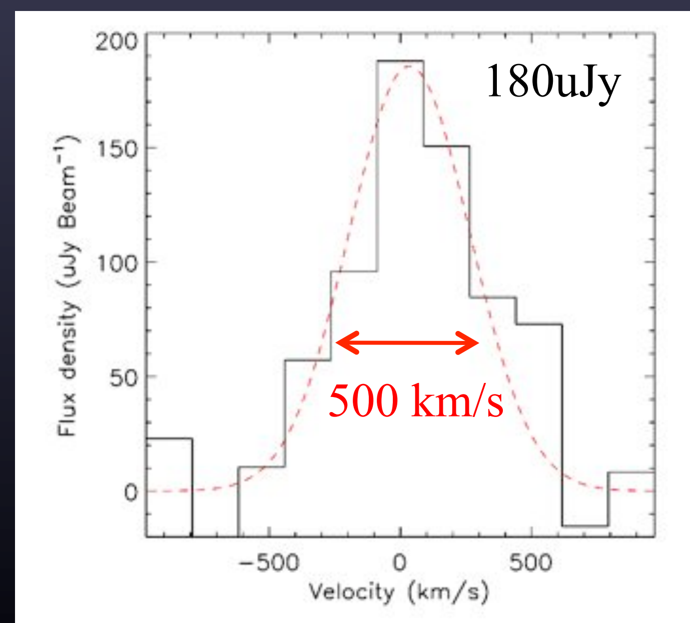
State of the Art: EVLA

- EVLA early science:

Approaching the Epoch of Reionization in CO !

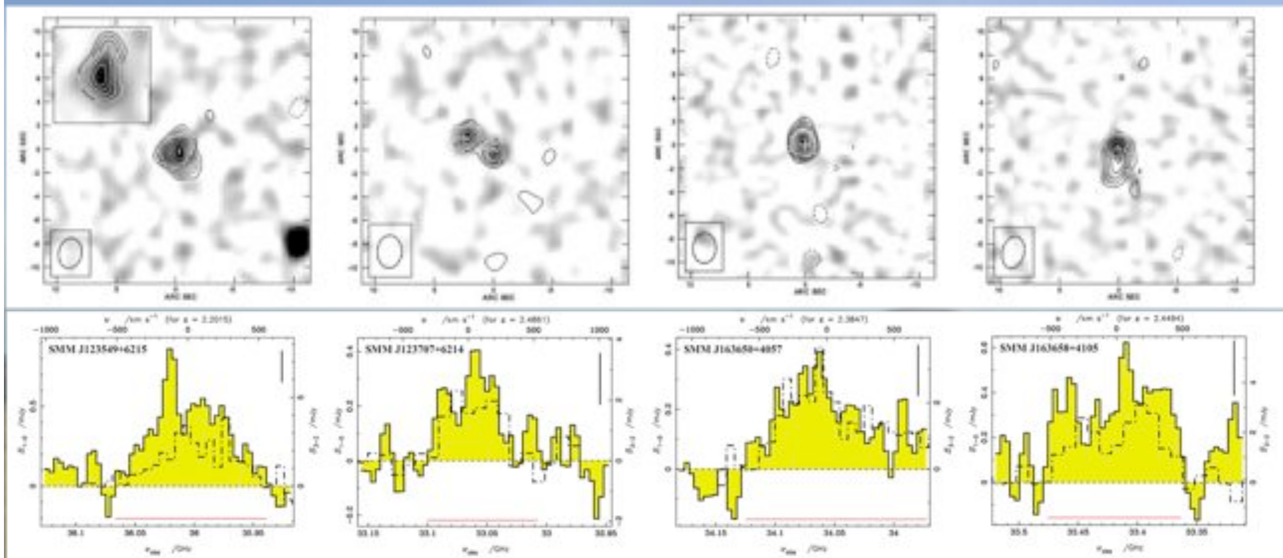
Approaching first light: molecular gas in z~6 quasar host galaxies
- Coeval formation of SMBH and massive galaxies within 1Gyr of Big Bang



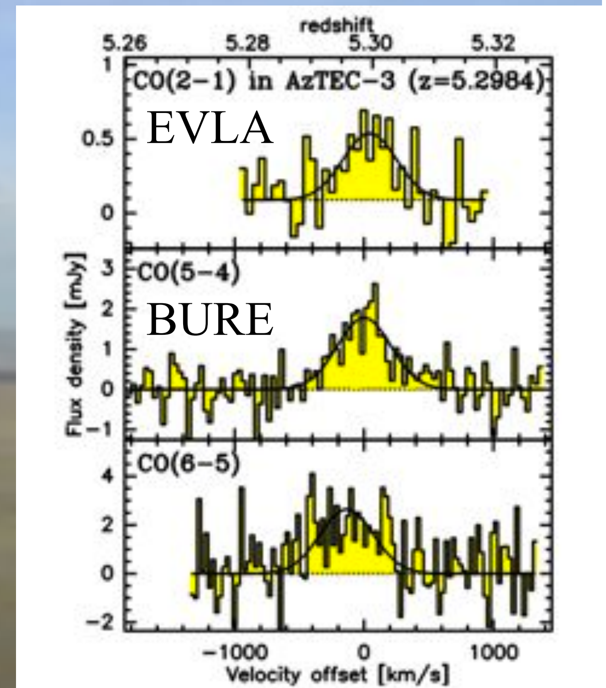


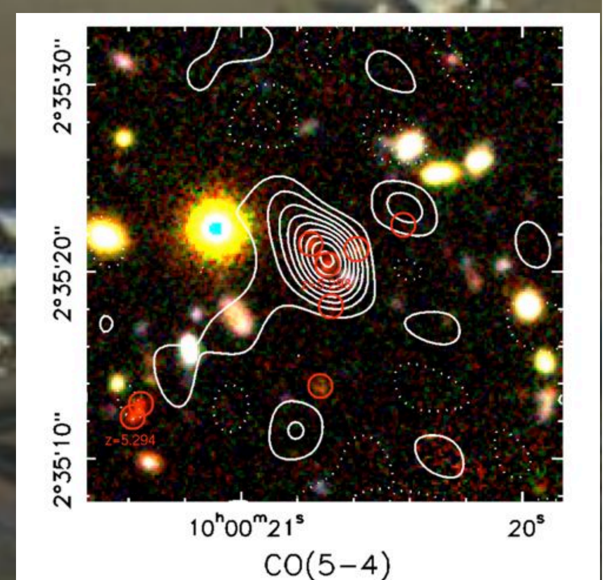
Wang, Wagg et al.

Blue Skies over the EVLA



Extended, low excitation CO in z~2.3 SMG (Ivison etal.)



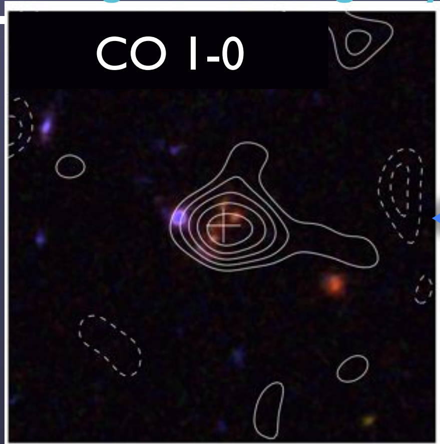


Multitransition CO study of most distant SMG z=5.3 (Riechers, Capak etal.)

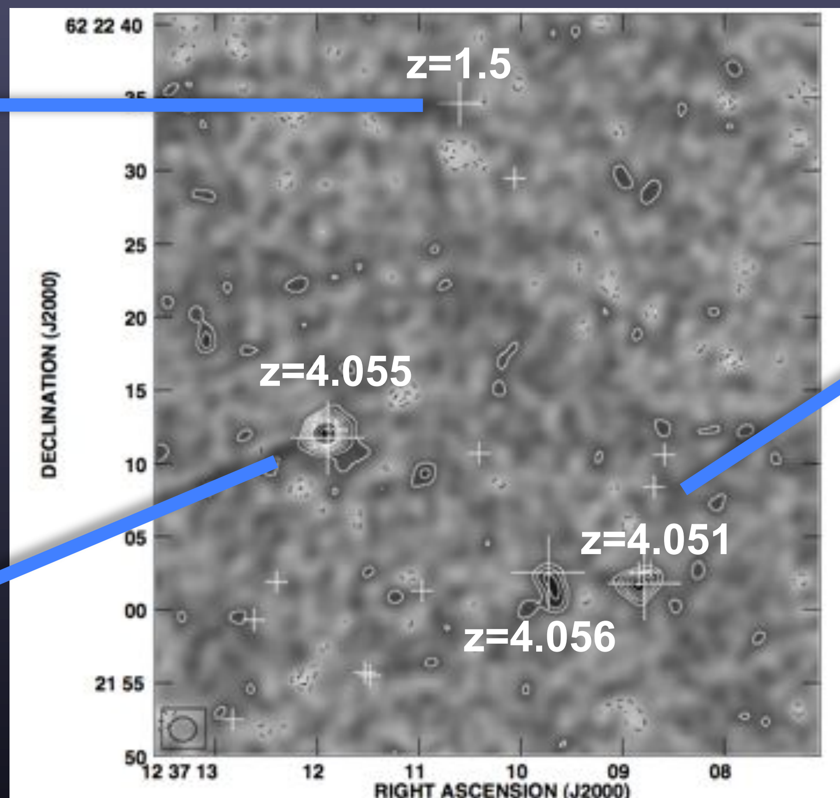
Courtesy C. Carilli

A Molecule-Rich Protocluster

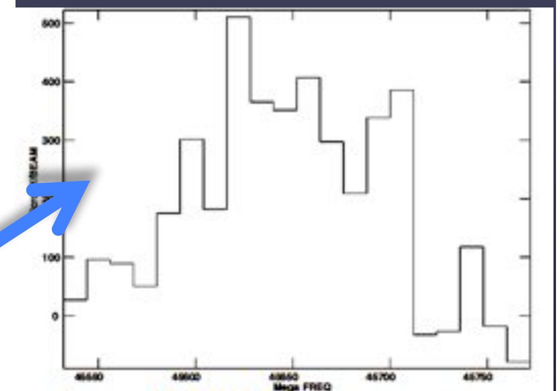
Foreground sBzK galaxy



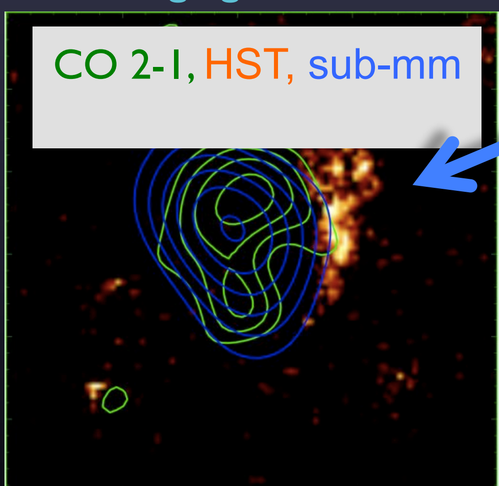
46 GHz Observations of GN20



CO 2-1 Spectroscopy



Imaging CO 2-1



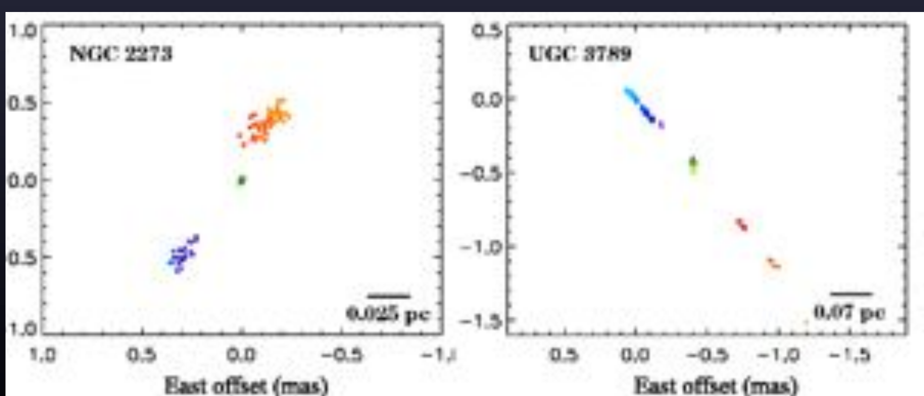
Wide Bandwidth = Large Redshift Range

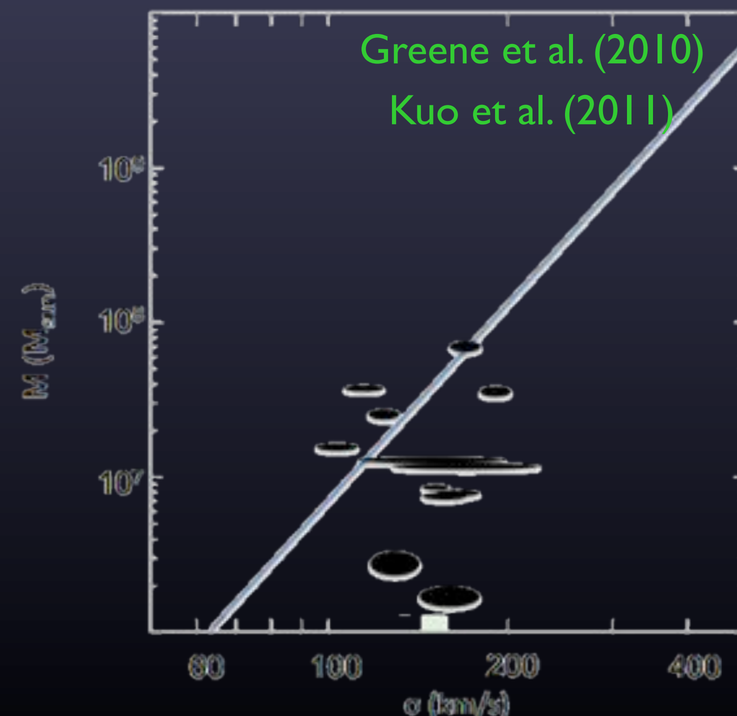
CARILLI ET AL. (2011)

Megamaser cosmology project
GBT/VLA/VLBA *Braatz, Kuo et al.*

- Goal: Measure Hubble constant
  - Determine geometric distance to AGNs hosting water maser disk through orbit modeling high velocity maser motions
  - Couple to redshift determined from systemic maser velocity
- Goal: Measure black hole masses precisely, find deviations from M-σ relation
  - 18 galaxies so far, seem to trend below relation
- First results from galaxies within the Hubble flow
  - suggest H_0=69±11 km/s

example maser spot maps





Radio Cosmology: Obscured Universe

I. Evolving Universe: High z molecular gas = 'fuel for galaxy formation'

- Low order molecular transitions: total and dense gas mass
- High spatial/spectral resolution = sizes and dynamics

Wide bands = large cosmic volume searches

II. <u>Obscured Universe: Broad band spectroscopic imaging of star formation and galactic nuclear regions</u>

- Multiple, key diagnostic lines

<u>Wide bands = more species</u>

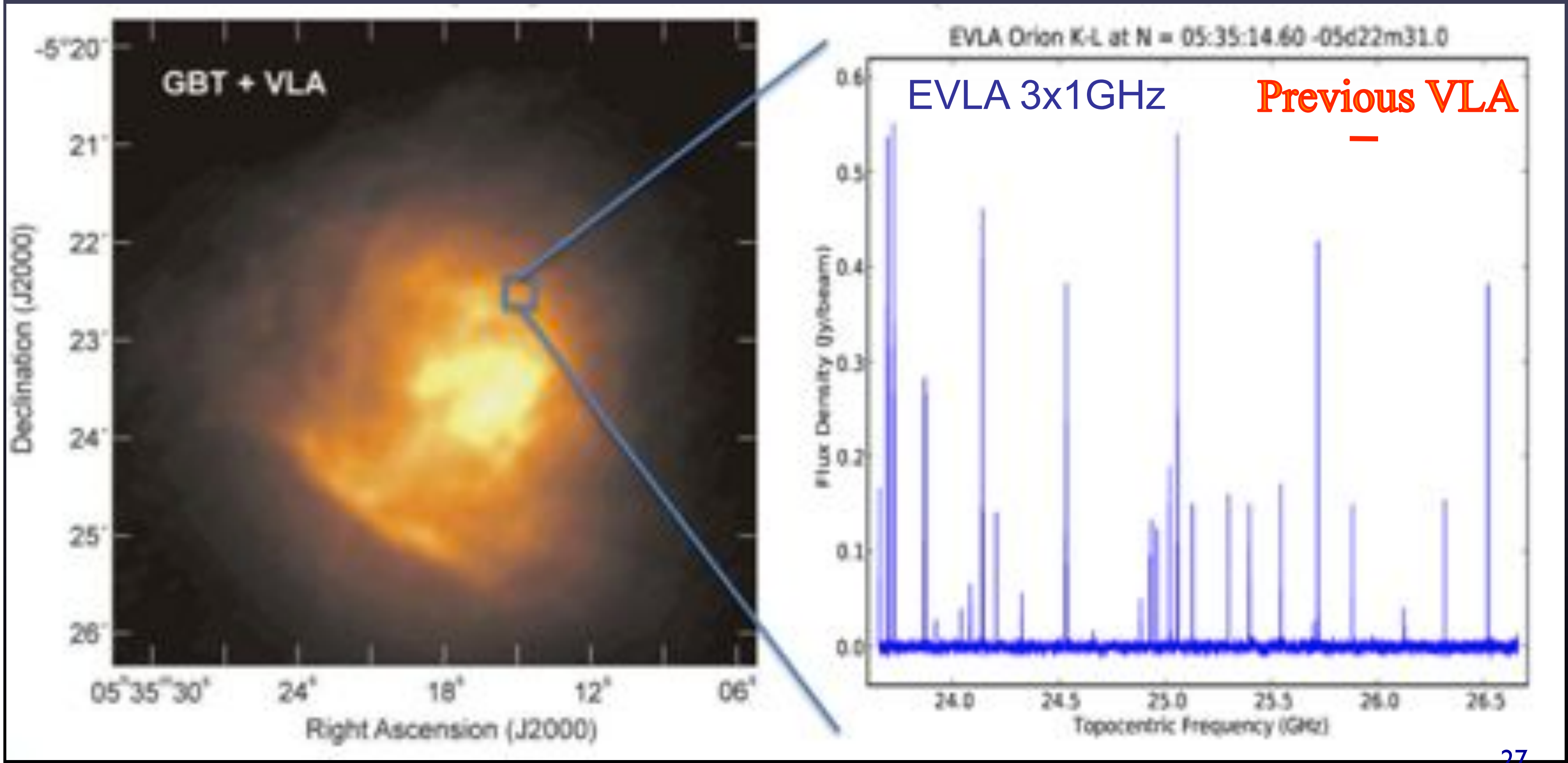
- Sub-arcsecond imaging

VLA starting to probe nearby obscured Universe

Future: extend to beyond Local Group (Coma or bust!)

Obscured Star Formation

Orion hot molecular core: The hot core lies in the molecular cloud behind the nebula. Hot cores are thought to be signposts of the earliest phase of massive star formation; rich chemistry, high densities and temperatures



Realizing Science: Magnetic Universe

I. Evolving Universe: High z molecular gas = 'fuel for galaxy formation'

- Low order molecular transitions: total and dense gas mass
- High spatial/spectral resolution => sizes and dynamics
- Wide bands => large cosmic volume searches

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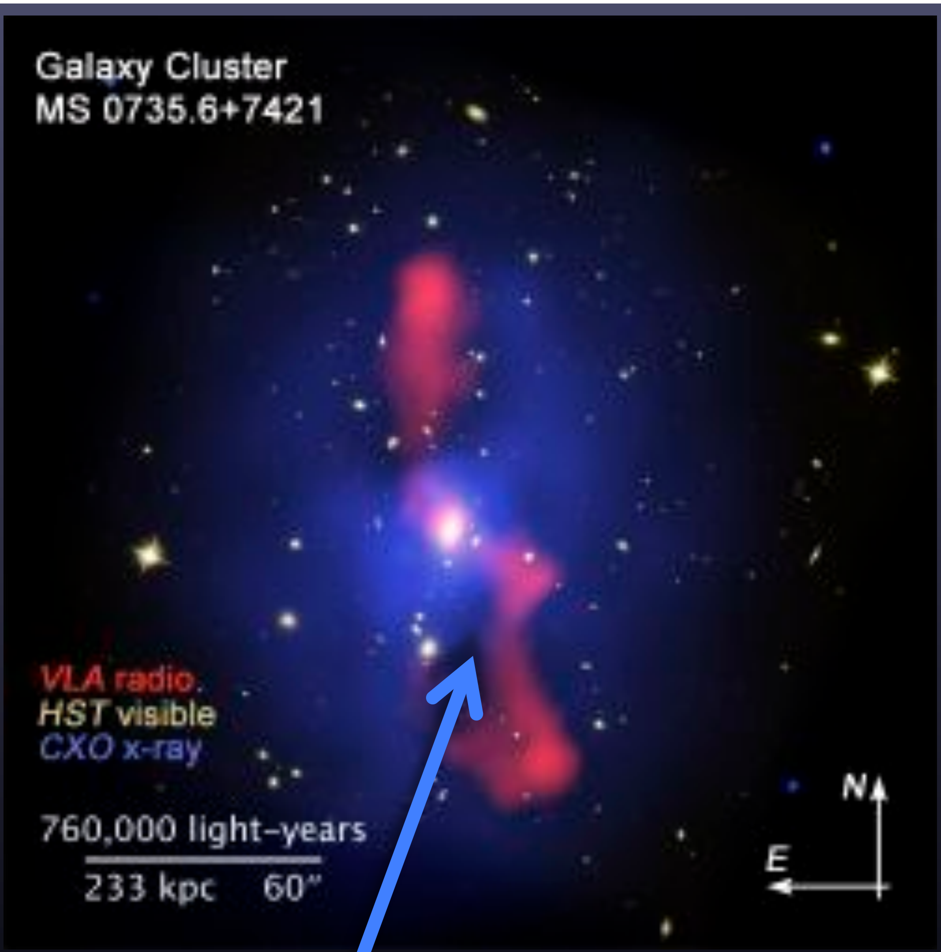
- Multiple, key diagnostic lines wide bandwidth = more species
- Sub-arcsecond imaging

III. Magnetic Universe: Tracing Cosmic Ray Acceleration

- Non-thermal emission fueled by extreme objects (SMBH,etc.)
- Polarization Imaging and rotation measure studies

Wide bands = continuum sensitivity and Faraday depth resolution

Role of B fields in Intercluster Medium

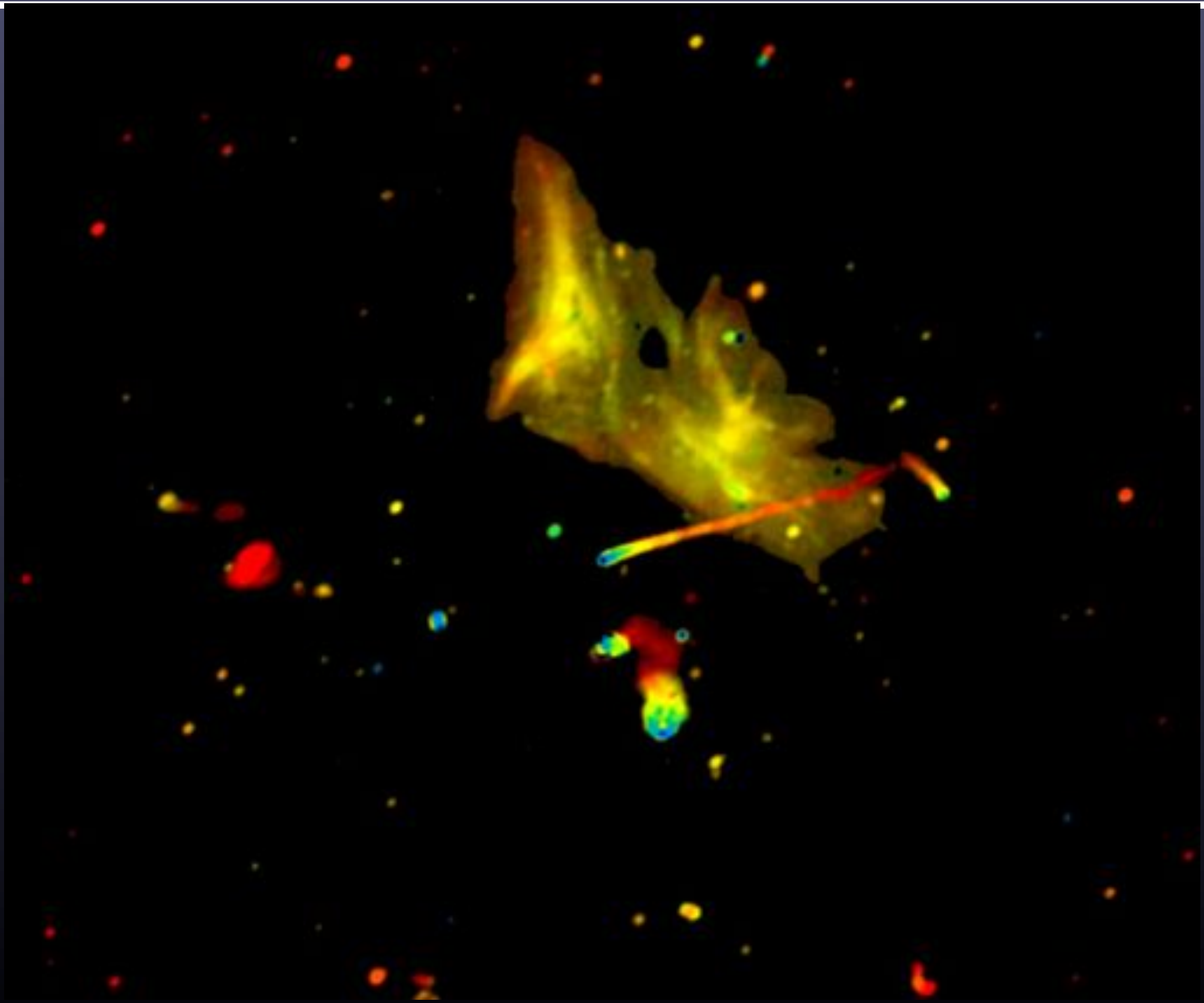


X-ray cavities correspond to radio lobes = feedback?

- Deep ignorance on origin and evolution of cosmic B fields
  - Affects cosmic ray transport
  - Role in cluster gas heating?
  - Trace galaxy/cluster interactions
- EVLA capabilities
  - Increased sensitivity to field direction and fractional polarization via synchrotron
  - Increased spectral resolution allows field strength estimates via rotation measure

Relics and jets in Abell 2256

- 1–2 GHz, 20-arcmin on a side; color corresponds to spectral index (Owen, Rudnick, Eilek, Rau, Bhatnagar, Kogan)
- Studies of the complex interactions between galaxies, AGN feedback, ICM, magnetic fields, and dark matter content of clusters
- Role of radio galaxies and relics in cluster evolution?



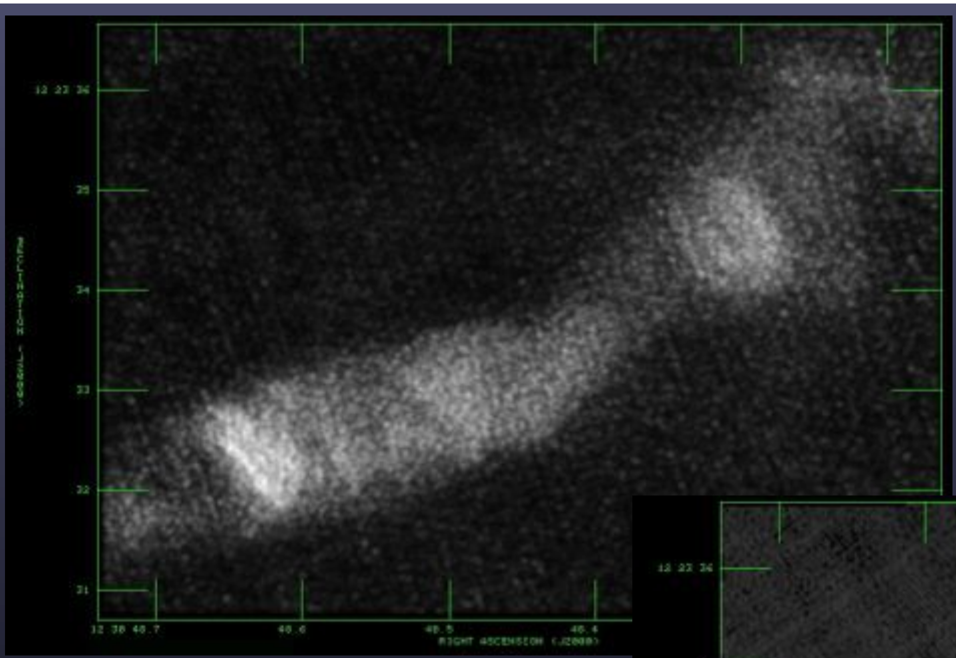
Local U: The jet of M87, then and now

Old VLA

44 GHz

50 MHz

bandwidth



EVLA demo science: F. Owen

study shocks, particle acceleration, and jet physics

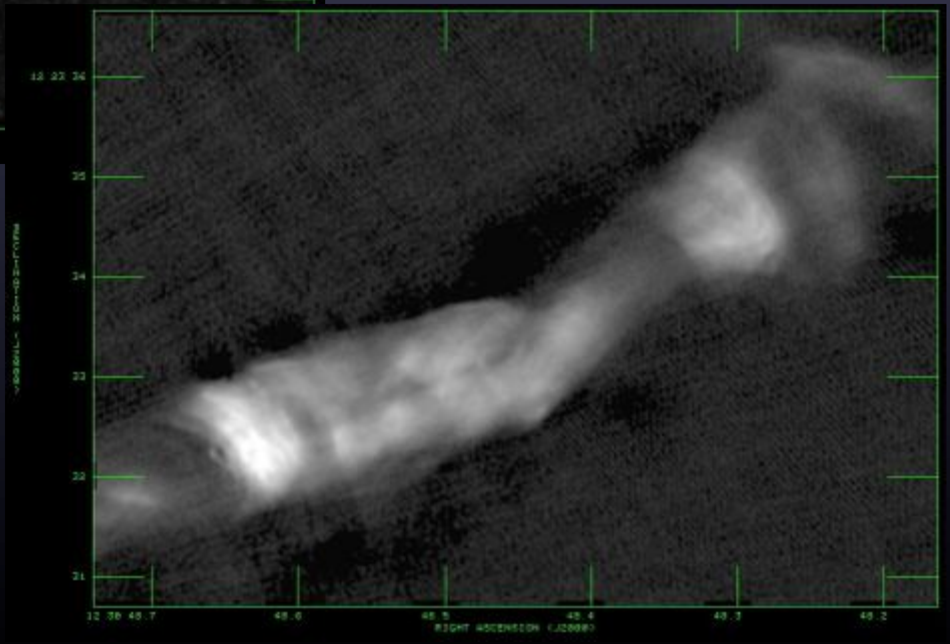
Improved imaging performance & sensitivity due to wider bandwidth

EVLA

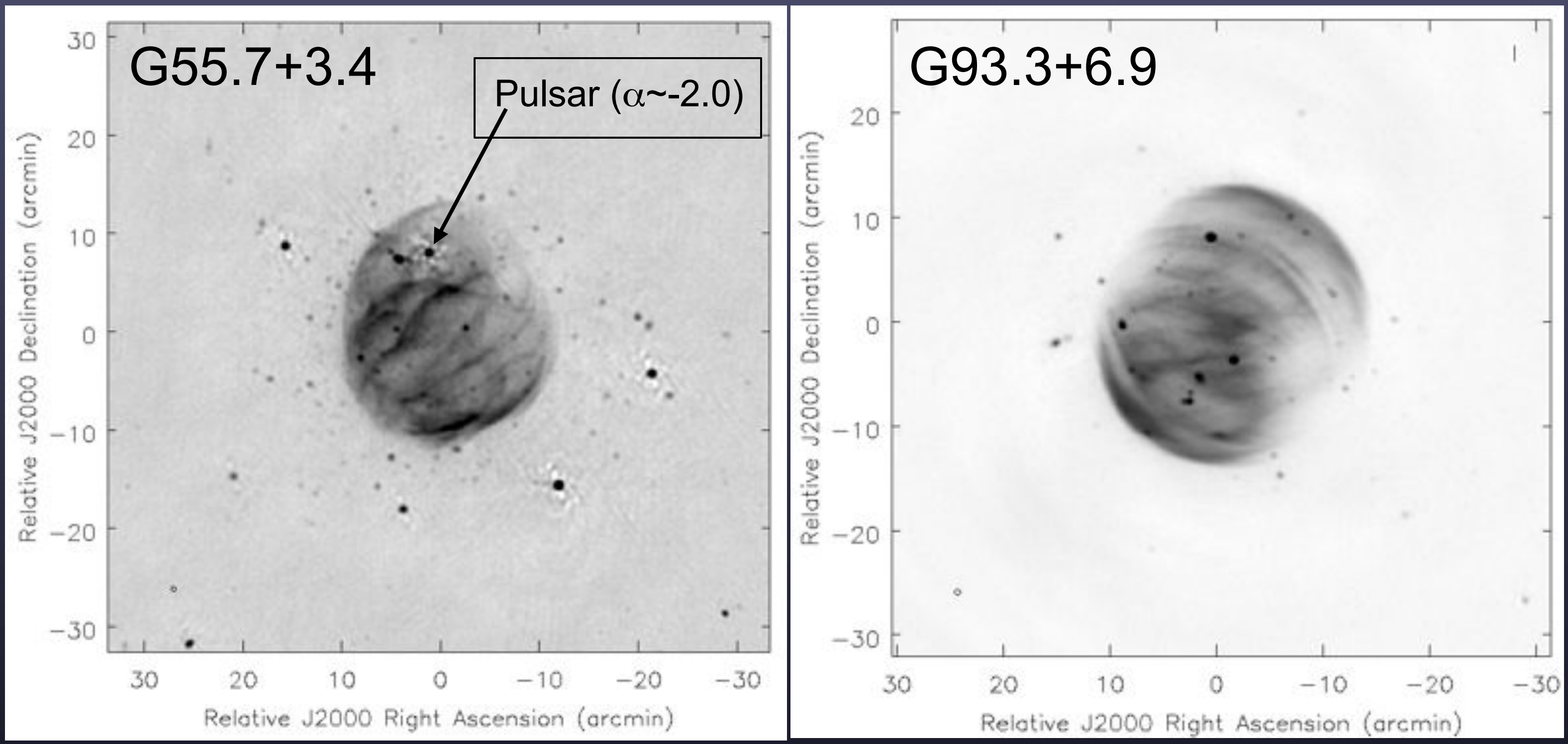
33 GHz

2GHz bandwidth

(8GHz soon!)



Closer to Home: Galactic SNR



Wide-band Galactic Plane survey pilot

(Bhatnagar, Green, Rau, Golap, Rupen & Perley)

Stokes-I images with EVLA @ 1-2GHz,

- Sites of cosmic ray acceleration
- Kinetic energy feedback into ISM

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- Multiple, key diagnostic lines   wide bandwidth = more species
- Sub-arcsecond imaging

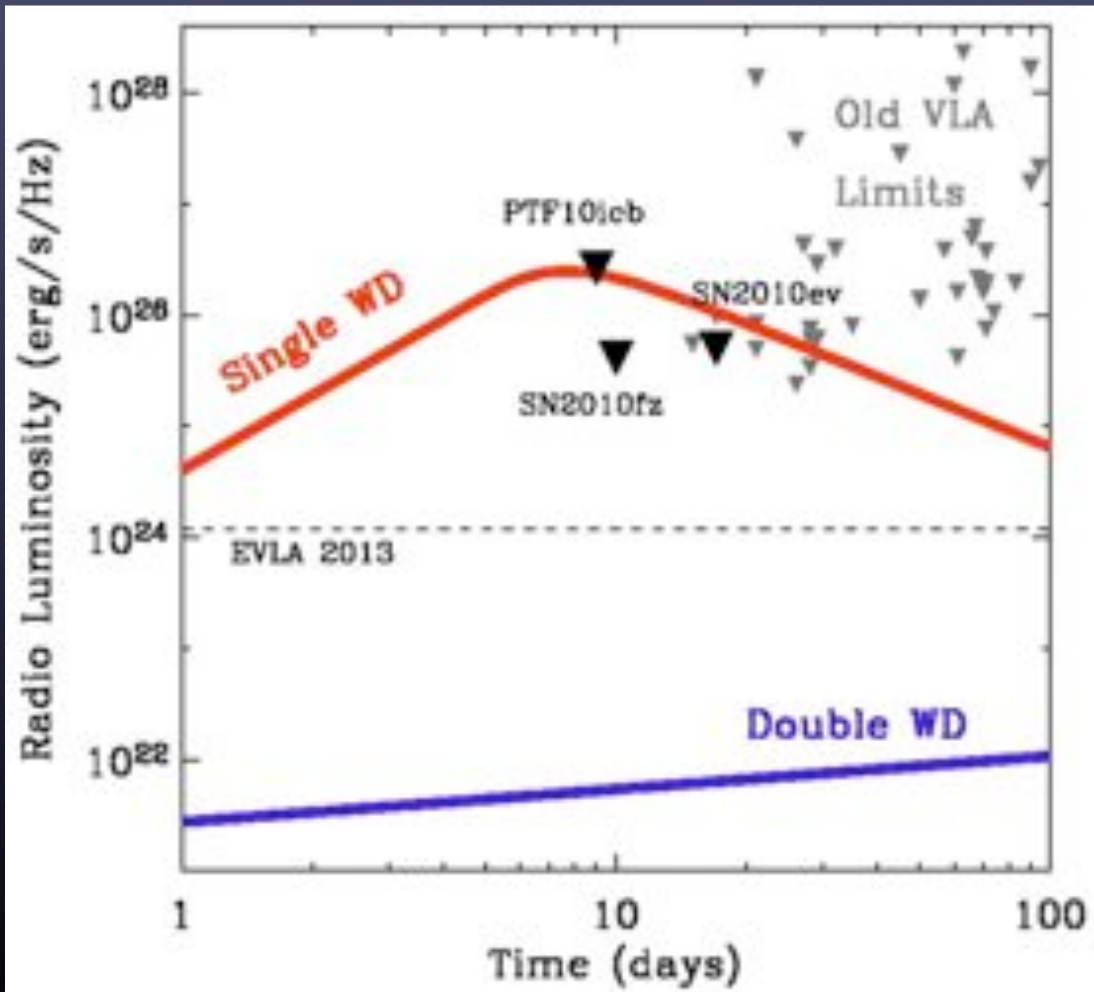
III. Magnetic Universe: Tracing Cosmic Ray Acceleration

- Continuum Bandwidth for imaging and rotation measure studies

IV. Transient Universe

- Explosive, impulsive, recurring events (pulsars, GRB, SNe, TDE, EM counterparts to Gravity Wave sources)
- **Bandwidth = sensitivity for survey speed, dynamic spectral signatures**

Transient Universe
Revealing the Progenitors of Type Ia Supernovae



EVLA Early Science

AS1020 (PI Soderberg)

10 hrs RSRO 4-configs.

Observations:
ToO's for all SNe Ia < 30 Mpc
(8 per year)

Single White Dwarf:
SN shock-accelerates
DONOR star's wind

Double White Dwarf:
SN shock-accelerates ISM

3 EVLA obs since April '10
PTF10icb, SN2010ev,
SN2010fz *(rms 10-20 uJy)*

Best limits to date, ***already at odds with SWD model...***

Gamma Ray Bursts: Calorimetry

- Fermi bursts and Radio Afterglows
  Cenko etal. 2010
  arXiv:1004.2900
  - Found by Fermi at higher energies than Swift bursts
  - Seem to be more luminous
  - Use modeling of X-ray, O/IR, and radio light curves to determine jet angle, beaming, and energy of burst

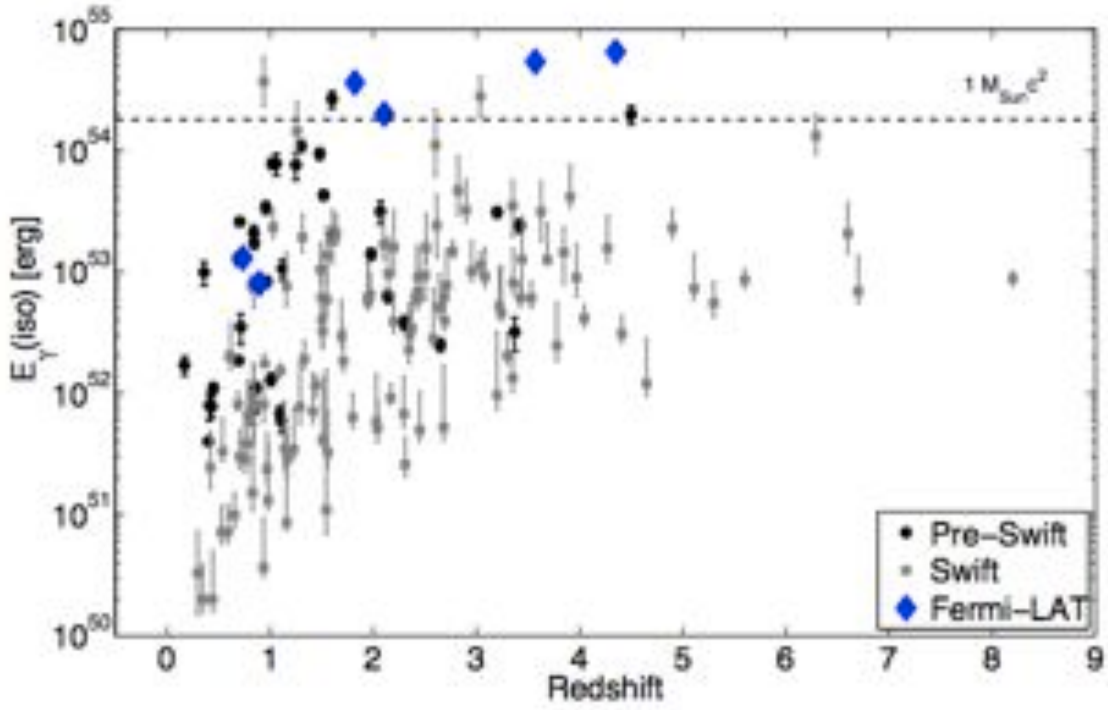


FIG. 1.— Prompt isotropic gamma-ray energy release ($E_{\gamma,\mathrm{iso}}$) of GRBs. With its soft, narrow bandpass (15–150 keV), *Swift* typically selects events with smaller isotropic energy release but larger opening angles than previous missions, which triggered predominantly in the MeV bandpass (Perna et al. 2003). GRBs detected at GeV energies with the *Fermi*-LAT all fall at the brightest end of the isotropic energy distribution, and must therefore be highly collimated to achieve a canonical beaming-corrected energy release of ~ 10^{51} erg. References: pre-*Swift*: Amati (2006); *Swift*: Butler et al. (2007); *Fermi*-LAT: Greiner et al. (2009), this work.

Gamma Ray Bursts: Calorimetry

- Fermi bursts and Radio Afterglows
  - Found by Fermi at higher energies than Swift, more luminous
  - Radio afterglow monitoring shows evidence for “jet break” at $\theta\Gamma\sim1$
  - Modeling of X-ray, O/IR, and radio light curves
  - Most energetic GRBs putting pressure on magnetar models vs MHD

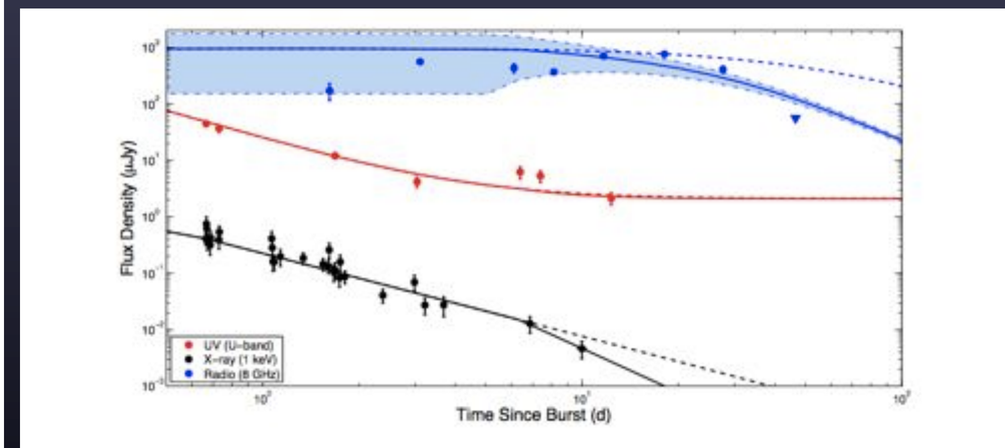
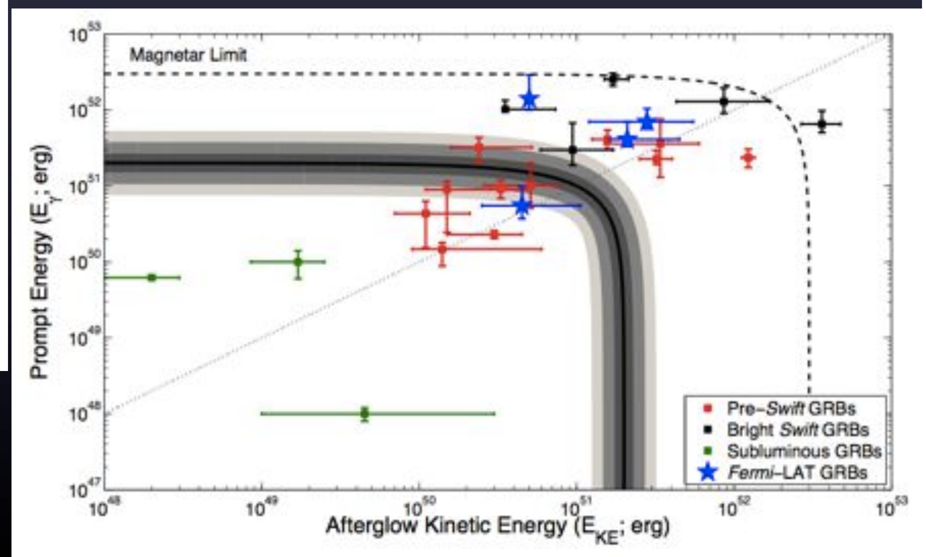


FIG. 4.— The broadband radio (blue), UV (red), and X-ray (black) light curve of GRB 090328. The best-fit model is plotted in solid lines (see Table 5 for parameters). The identical model parameters for an isotropic explosion are plotted as the dashed lines. The radio light curve is not very well fit at early times, although it likely suffers from strong interstellar scintillation (light-blue shaded region). In this case a jet break is required by the data to fall at $t \gtrsim 10$ days.

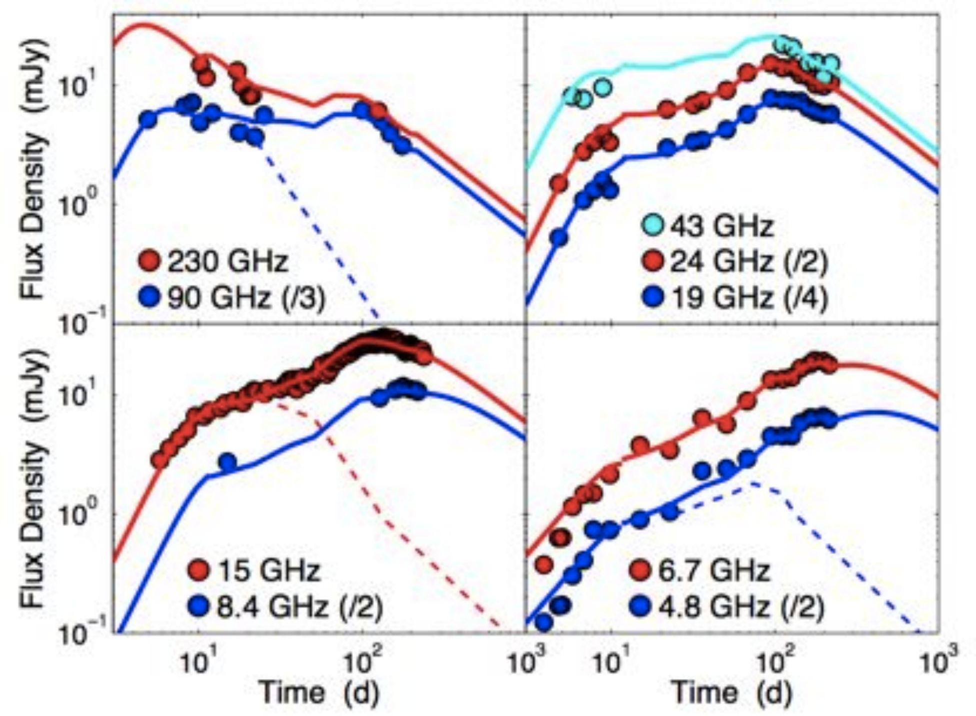
Holy Grail of GRBs:
Very high redshift GRB
Current winner z=8.3

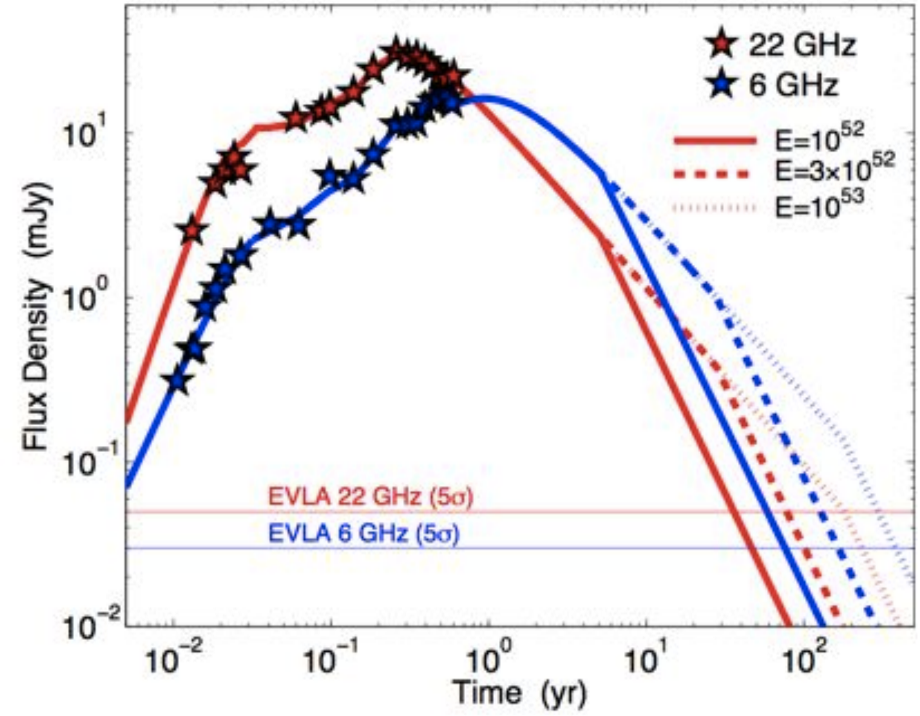


From Cenko etal. 2010
arXiv:1004.2900

A Tidal Disruption Event?

- Swift J164449.3+573451 TDE candidate
  - Radio: Zauderer etal. 2011, Berger etal. 2011 (figs below)
  - Chain of evidence points to transient accretion of stellar mass onto SMBH in a galaxy core
  - Radio emission eventual calorimeter

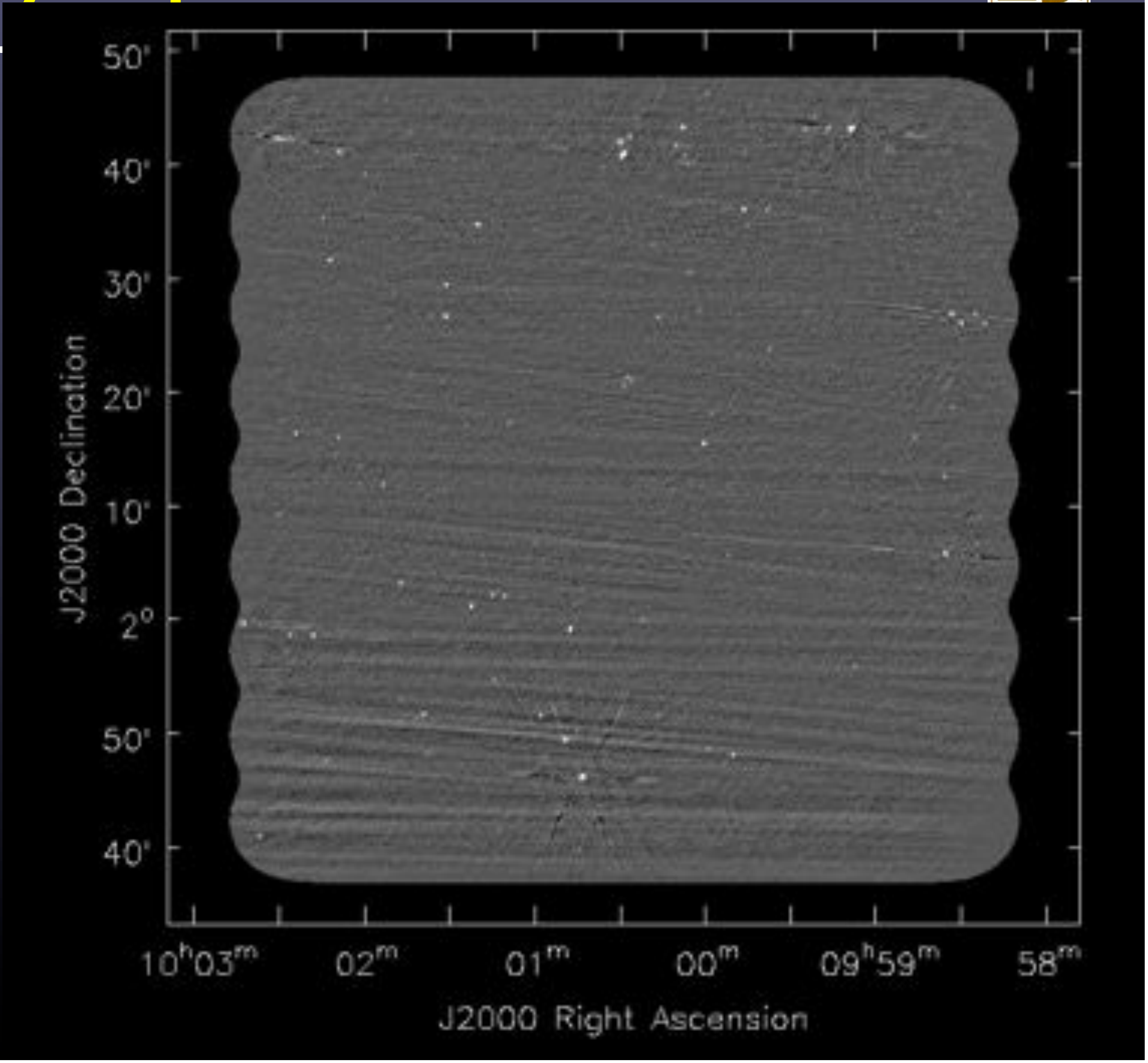




VLA Survey Capabilities

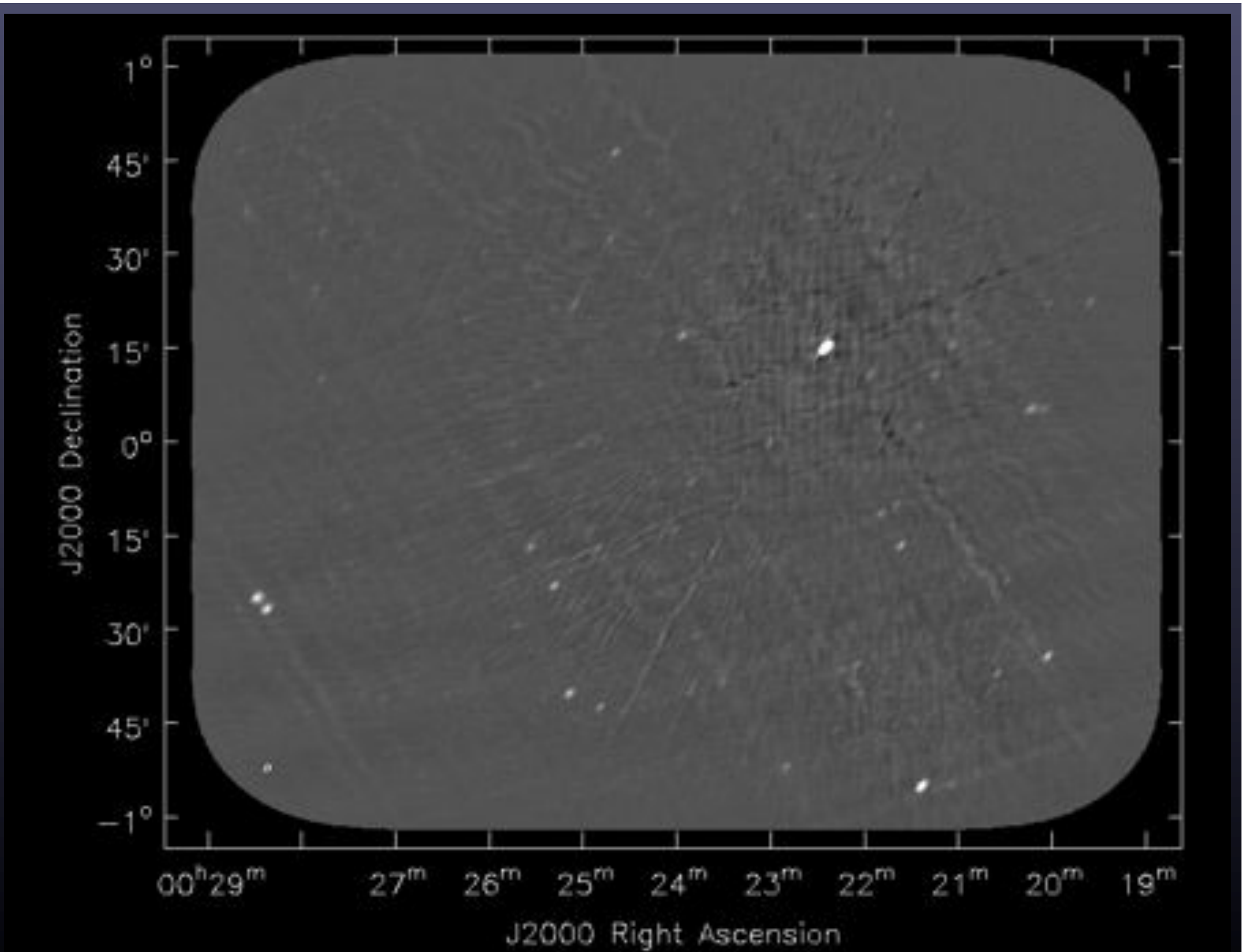
- On-the-fly mosaics
  - cover wide areas quickly
  - reconstruct mosaic during imaging (CASA)
  - 100 sq. degrees to 100μJy (1σ) in 40ksec (11h)

TRSR0015
C-band 1hr SB
4.2-5.2 + 6.5-7.5GHz
1.36 square degrees
driven scans
270 phase centers
50μJy rms
COSMOS field



EVLA Survey Capabilities

- On-the-fly mosaics
  - cover wide areas quickly
  - reconstruct mosaic during imaging (CASA)



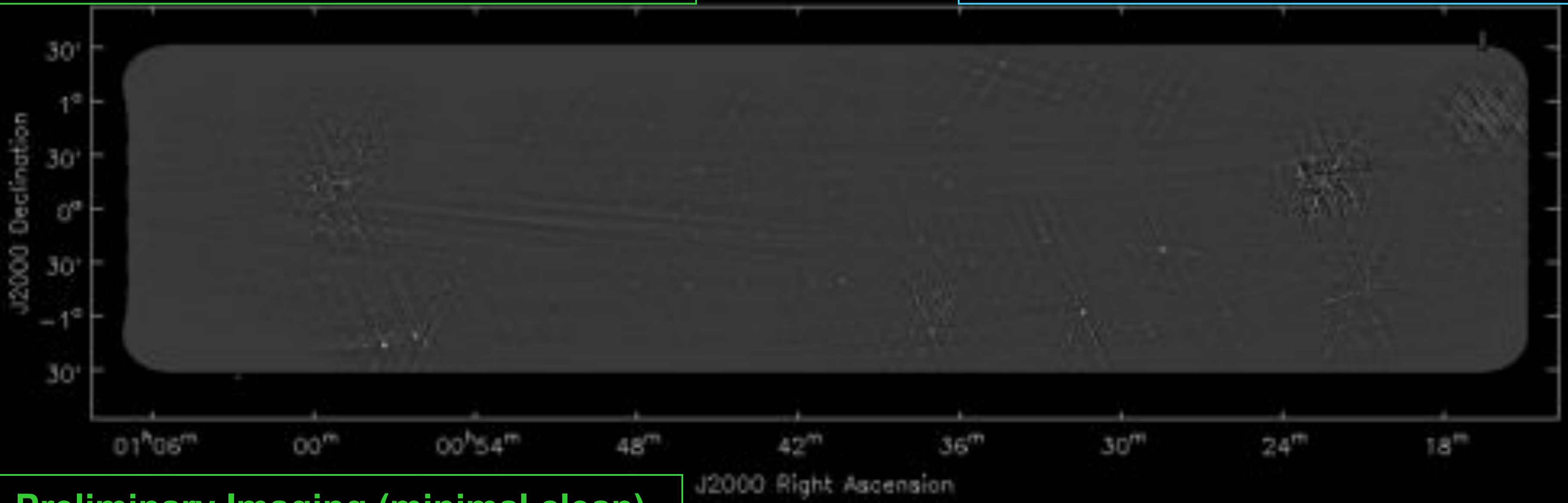
TRSR0045
L-band 1hr 1400MHz
2deg x 2deg
5 x 8m x 20’ drift scans
150 phase centers
1.7mJy rms 1400:1
Stripe82

Pilot Project: more of Stripe 82

- EVLA project 11B-203 (Myers,Sievers etal.)
  - 12.5deg x 3deg ACT/SDSS equatorial stripe (37.5 sq.deg)

Eventual Goal:
120deg x 3deg = 360 sq.deg

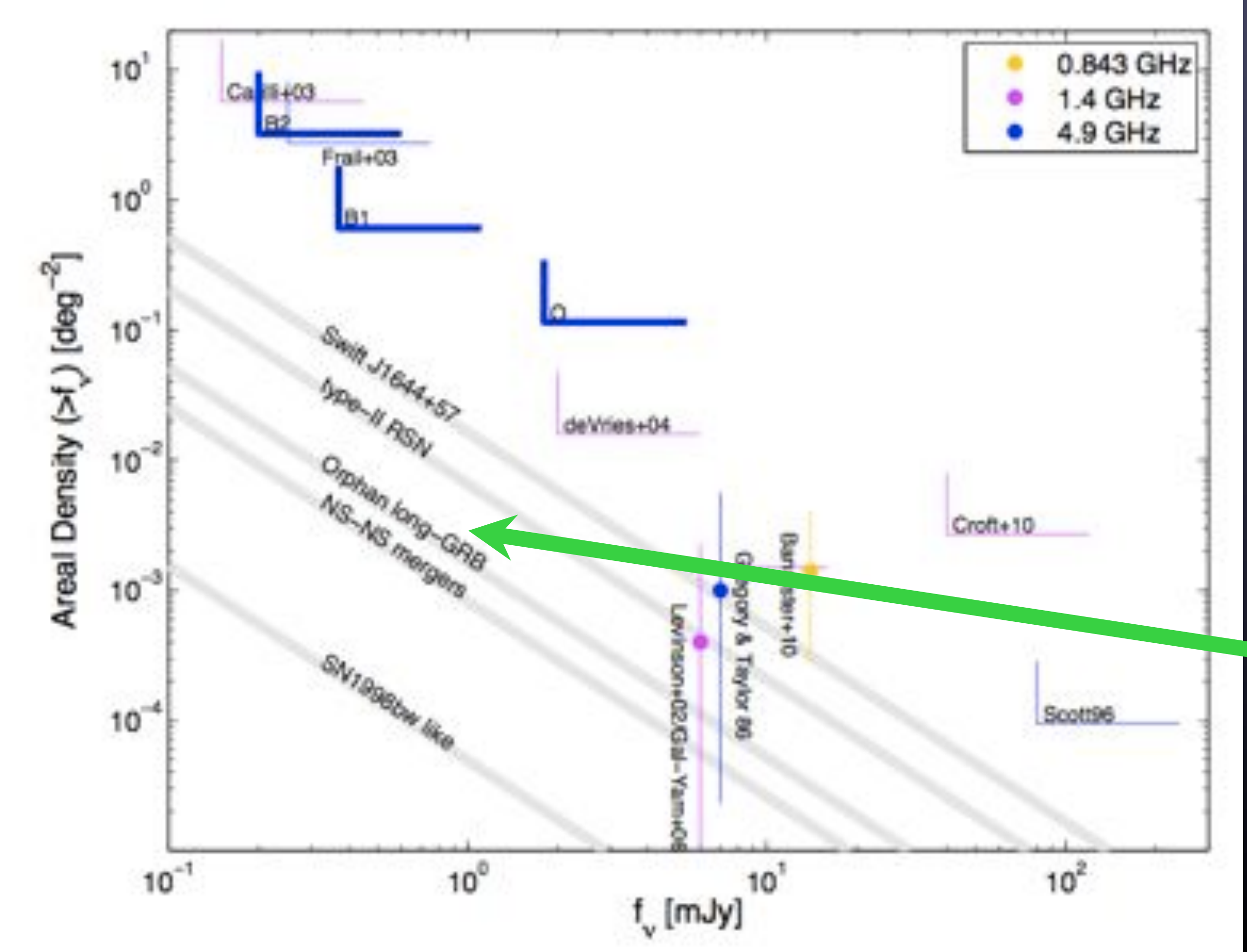
11B-203 L-band 8hr 1400MHz
12.5deg x 3deg
On-the-Fly (OTF) drift scan



Preliminary Imaging (minimal clean)
128MHz our of 1GHz only
~1mJy rms (artifcacts dominate)

Synoptic Radio Surveys

- Areal density vs. Flux density



Frail etal. 2011
ArXiv:1111.0007

Goals for VLA Survey
>10sq.deg at 0.1 mJy
>300sq.deg at 1mJy

Lessons Learned
These need to be 10σ limits from archival data!

The VLA Survey Data Challenge

- A "Big Data" problem?
  - The raw (post-correlation) raw data rate from current EVLA is ~50MB/s (can be few times higher near future) or ~200GB/hour (4TB/day). Not a big data problem.
  - However, to image the FOV in A-config from 1-2GHz out to first sidelobe (common) takes 1 Gpix. You can get one of these every 1 second. In 1024 channels (w/o averaging). That's potentially a 1 Tpix/sec!
  - For reference LSST has 3.2Gpix that can be read out every 2 sec but a single "channel".
  - EVLA imaging is even now potentially a "huge data" problem when looking for transients! Averaging is necessary.

The VLA and Radio Sky Surveys

- The Jansky Very Large Array (VLA) provides new and powerful capabilities for radio astronomical surveys as well as multi-wavelength follow-up observations.
- The VLA now can be a proving ground for Radio Synoptic Sky Surveys and pave the way for future surveys.
- We must fully utilize existing and near-term facilities (e.g. ALMA, EVLA, GBT, ASKAP, MeerKAT, etc.) if we contemplate large new facilities.

Future Radio Cosmology

To 2020 and Beyond

Radio Sky Surveys: A Program

- Building on a survey legacy from 3C onward
  - VLA surveys: NVSS, FIRST, VLSS, …
  - plus the standard deep fields (COSMOS, etc.)
- Radio Sky Survey Components
  - continuum (polarimetric) surveys: wide-band wide-field
  - spectral imaging surveys: wide-band wide-field spectra
  - spectral line (species/redshift) surveys: wide-band spectra
  - time domain surveys: high time resolution
  - synoptic sky surveys: high instantaneous sensitivity
  - dynamic spectral surveys: high time-frequency resolution

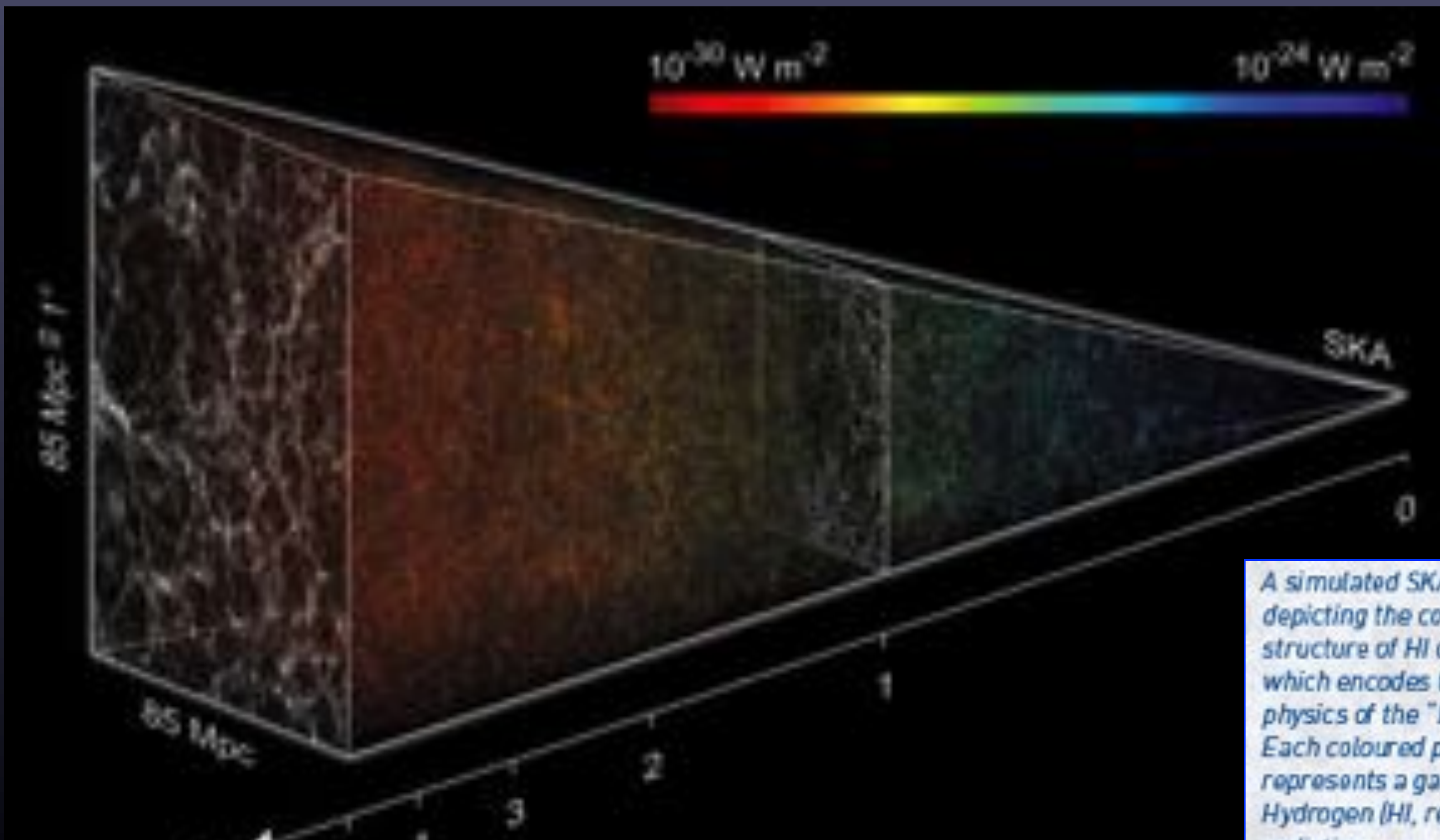
  survey program components need not be on same facility!

Instrumenting Radio Science: 2020+

- Ultimate Radio Cosmology
  - m: HERA-III (convergence of PAPER,MWA,LOFAR)
  - sub-m: the Square Kilometre Array (SKA)
  - cm: the "North America Array" (NAA)
- Towards a North America Array
  - future evolution of NA facilities (EVLA, GBT, VLBA, &c)
  - collecting area: 10 x EVLA (half on "VLB" baselines?)
  - key science ("SKA High"):
    - astrometry
    - "ALMA science" at high-z and in obscured regions
      - detailed (sub-arcsecond) imaging as well as detection
  - for more info:
    - http://www.nrao.edu/nio/naa/

Final Fantasy MMXXV: SKA

- Billion Galaxy HI survey to z > 1.5



A simulated SKA observing cone depicting the complex filamentary structure of HI on cosmic scales, which encodes the mysterious physics of the "Dark Universe". Each coloured pixel in the cone represents a galaxy emitting neutral Hydrogen (HI, rest-frame 21-cm) radiation. (Credit: Danail Obreschkow (Oxford) and the SKADS Sky Simulation team.)

Astro2010 white paper: Myers et al.

arXiv:0903.0615

The Square Kilometre Array Program

- The SKA is an international program to build the next generation of large radio arrays
  - SKA-low : 10-300 MHz (2012 decision: Australia)
    - Epoch of Reionization (EoR) and Dark Ages Telescope
    - Pathfinders/Precursors: MWA, PAPER, LWA, GMRT, LOFAR
  - SKA-mid : 0.3-10 GHz (2012 decision: South Africa)
    - a "Radio Synoptic SKA" for galaxy surveys
    - Pathfinders/Precursors: EVLA, ALFA, ATA, ASKAP, MeerKAT
  - SKA-high: 1-50 GHz (2020+ goal: North America)
    - Cosmic Star Formation and the "Cradle of Life"
    - Pathfinders/Precursors: EVLA, GBT, ALMA
    - The North America Array for 2025+